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Technical Report

(6) TEST OF GERMAN SAND-TYPE FILTER

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TEST OF GERMAN SAND-TYPE FILTER

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(10) by

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ABSTRACT

Presented is a sand filter

~~The shelter equipment developed by the Artos Machinery Company of Germany specifies a sand filter which the U. S. Naval Civil Engineering Laboratory~~ evaluated with respect to ventilation characteristics and effectiveness in protecting a shelter from the hot blast of a nuclear explosion. Tests indicated an airflow of 4 cfm per square foot of filter area for a 36-~~inch~~ in. depth of sand, 6 cfm for a 24-inch depth, and 12 cfm for a 12-~~inch~~ in. depth when the pressure drop is 1-~~inch~~ in. water-gaged. Special equipment was built to release compressed air to simulate the blast from a nuclear explosion. A model shelter consisting of a steel tank was connected to the air-blast device through an 8-~~inch~~ in.-diameter sand filter. The filter proved to be reasonably effective in attenuating blast when subjected to overpressures up to 100 psi with a positive time duration of about 2 seconds. However, the effectiveness varied with changes in the size of sand grains even though the changes were within the filter specifications.

The heat-absorbing characteristics of the sand were studied under conditions similar to a nuclear blast, by subjecting the filter to blasts of hot pressurized air. Heat-absorption characteristics were also studied, in 24-hour tests simulating night and day, when ventilating air of varying temperatures was passed through the filter. The sand proved to be an excellent heat absorber, maintaining the outlet temperature at an acceptable level.

~~Since~~ a A sand filter is not a positive closure device, it has a typical response for a given impulse and the response depends on its physical characteristics. Consequently, if a filter is to be classified as safe for a certain overpressure and time duration, the filter as a unit should be pretested or the sand must be very carefully graded and matched against control samples.

## INTRODUCTION

Following World War II the use of sand filters for shelter-ventilation systems was investigated and to some extent adopted in Germany and other parts of Europe. Consequently, information on the size of sand grains, on the depth of sand, and on various other characteristics was available but the capacity of the sand to protect against blast and heat was uncertain. NCEL was assigned a task to obtain more extensive data on the normal ventilation characteristics and to determine if sand could protect the shelter from the hot blasts of nuclear explosions and heated ventilating air resulting from fires. This information was obtained by three separate experiments; the first deals with ventilation characteristics under normal operating conditions, the second with blast attenuation, and the third with heat absorption. This work was partially sponsored by the Defense Atomic Support Agency through the Bureau of Yards and Docks.

## VENTILATION FLOW CHARACTERISTICS

### Description of Equipment

Figure 1 shows the method used to determine airflow rates and pressure drops through the sand filter. Because they are more accurate, compressed air and rotameters were used in preference to a pressure fan and pitot tube. The box holding the sand was 1 square foot in cross section and was deep enough to test 40 inches of sand. The sand was supported by a perforated steel plate, a screen, and 2 inches of gravel.

The sand used in this test conformed to the Artos Machinery Company specifications: 80 to 90 percent from 1 mm to 3 mm, 5 to 15 percent from 0.2 mm to 1 mm, and up to 5 percent less than 0.2 mm.

### Test Procedure

A layer of 12 inches of sand was placed on the gravel support and vibrated with a concrete vibrator. Compressed air was then allowed to flow through the sand, and the airflow rate was measured by the rotameter and the static pressure drop by a micrometer. This procedure was repeated for 24 and 36 inches of sand, with 6 to 10 readings for each depth.

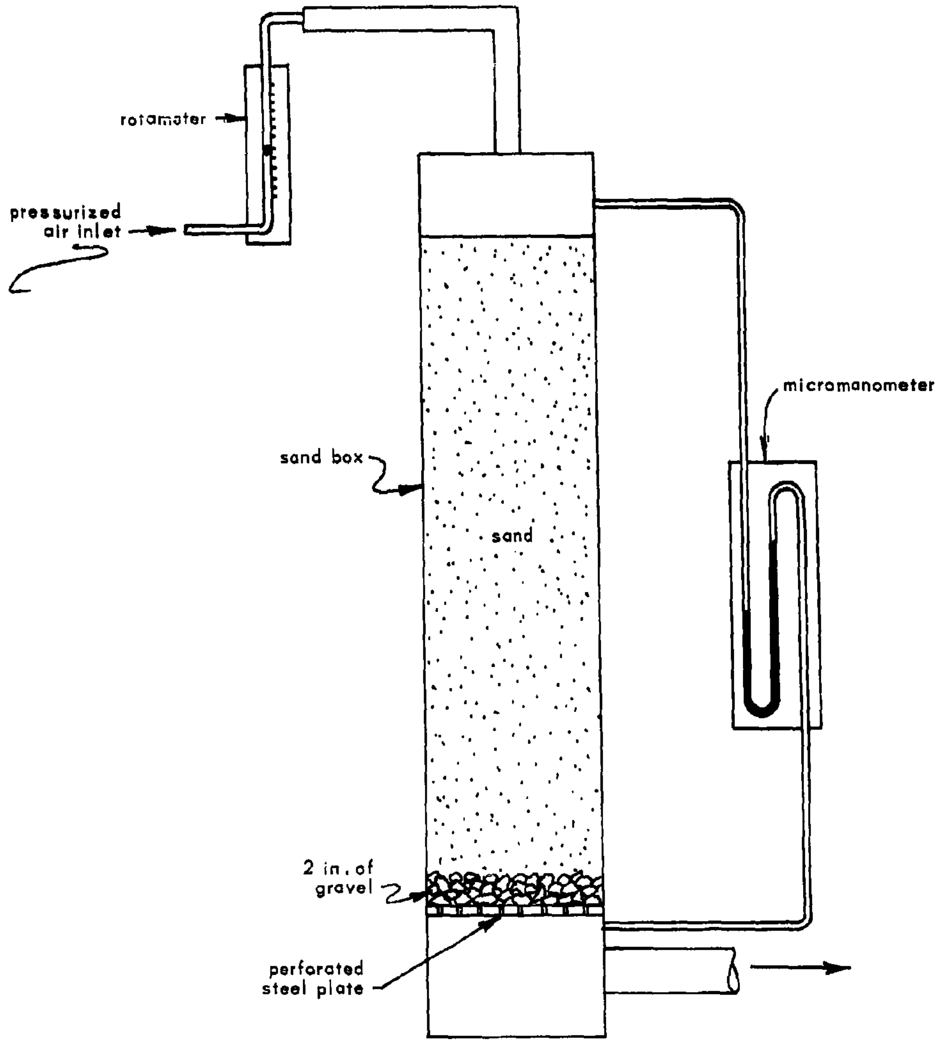


Figure 1. Determination of airflow rate through sand.

Test Results

The data from these tests is shown in Table I. At a 1-inch static pressure drop (probably the limit for hand-operated equipment) the flow is almost inversely proportional to the depth. Table II shows the filter cross-section areas which would be required for various shelter populations based on a ventilation rate of 3 cfm per person and a 1-inch static pressure drop. Table II emphasizes the large areas required for 100 people, particularly when a 36-inch depth of sand is necessary.

Table I. Static Airflow Rates Through Sand (in cfm per sq ft of filter area)

| Sand Depth (in.) | Pressure Drop (in. of water) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 | 1.2 | 1.4 |
| 12 | 2.7 | 5 | 7.2 | 9.5 | 12 | 14 | 16 |
| 24 | 1.3 | 2.3 | 3.6 | 4.8 | 6 | 7 | 8 |
| 36 | 1 | 1.8 | 2.5 | 3.3 | 4 | 4.8 | 5.6 |

Table II. Filter Cross-Section Area Required for Ventilation (at 3 cfm per person and 1 in. W. G. static pressure drop)

| Sand Depth (in.) | No. of People in Shelter | | | |
|---|---|---|---|---|
| | 25 | 50 | 75 | 100 |
| 12 | 6.25 $ft^2$ | 12.5 $ft^2$ | 18.75 $ft^2$ | 25 $ft^2$ |
| 24 | 12.5 | 25 | 37.5 | 50 |
| 36 | 18.75 | 37.5 | 56.2 | 75 |

## BLAST ATTENUATION

If a sand filter were built into the ventilation system of a shelter and tested in the field with a nuclear bomb, the shock wave emanating from the bomb and traveling somewhat faster than the speed of sound would approach the filter like a wall of compressed air. As the wave front approached, the overpressure would rise very rapidly to a maximum. As the wave front passed, the pressure would taper off to zero and become negative. The filter would therefore be subjected to a sudden peak overpressure followed by diminishing pressure. The magnitude and duration of the overpressure depends on the size of the bomb and the distance from ground zero to the point of measurement. The positive phase of a nuclear blast can be simulated on a small scale by using compressed air. A model (Figure 2) was built in which a large steel tank, called an Air Blast Device, held the compressed air, and another steel tank, called the plenum chamber, represented a shelter. A sand filter connected to this plenum chamber was subjected to various overpressures.

Rather than a true model it was necessary to design an adequate model in which the depth of the filter and characteristics of the sand were the same as the prototype. The cross-sectional area of the filter and volume of the plenum were reduced in scale by equal amounts. All of the quantities pertaining to the dynamic load, including the rise time and overpressure, were scaled the same in the model as in the prototype. Factors and pi terms for the dimensional analysis are shown in Table III. There are an infinite number of shelter-to-filter combinations; Table IV shows those tested in this experiment. The ventilation rates are based on a 1-inch water pressure drop.

Table III. Dimensional Analysis

| Factors | | Pi Terms |
|---|---|---|
| $u$ | velocity of air | |
| $q$ | overpressure applied to filter | $\frac{q}{\rho u^2}$ , $\frac{v_1}{v_2}$ , $\frac{p}{q}$ |
| $p$ | pressure rise in plenum | |
| $\mu$ | viscosity | |
| $a$ | area of filter | |
| $v_1$ | volume of filter | $\frac{\rho u v_1}{\mu a}$ , $\frac{u}{g\tau}$ |
| $v_2$ | volume of plenum | |
| $\tau$ | time | $\frac{u^2 a}{g v_1}$ , $\frac{\rho u^2 \tau}{\mu}$ |
| $g$ | acceleration of gravity | |
| $\rho$ | density of air | |

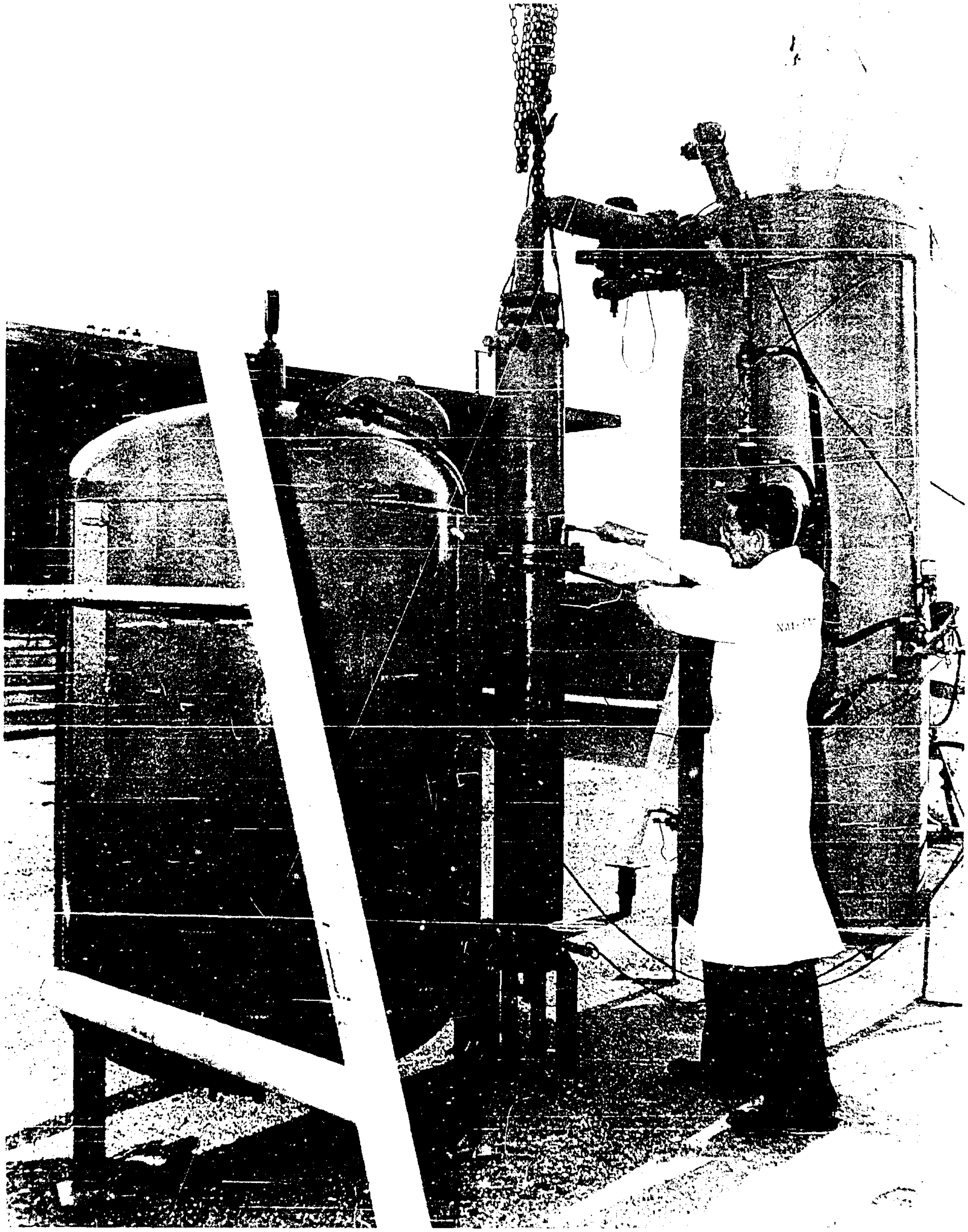

Figure 2. Model and Air Blast Device.

Table IV. Shelter-to-Filter Combinations

| Filter Depth (in.) | Shelter Volume / Filter Area (cu ft/sq ft) | 3 cfm per Person | | 5 cfm per Person | |
|---|---|---|---|---|---|
| | | Space per Person (cu ft) | Filter Area per Person (sq ft) | Space per Person (cu ft) | Filter Area per Person (sq ft) |
| 12 | | 22 | 0.25 | 38 | 0.417 |
| 24 | 88 [1] | 44 | 0.50 | 76 | 0.834 |
| 36 | | 66 | 0.75 | 114 | 1.250 |
| 12 | | 33 | 0.25 | 56 | 0.417 |
| 24 | 132 [2] | 66 | 0.50 | 112 | 0.834 |
| 36 | | 99 | 0.75 | 168 | 1.250 |
| 12 | | 44 | 0.25 | 75 | 0.417 |
| 24 | 176 [3] | 88 | 0.50 | 150 | 0.834 |
| 36 | | 132 | 0.75 | 225 | 1.250 |

1/ Based on 8-inch-diameter filter and 30-cubic-foot plenum.

2/ Based on 8-inch-diameter filter and 45-cubic-foot plenum.

3/ Based on 8-inch-diameter filter and 60-cubic-foot plenum.

## Description of Air-Blast Device

Figure 3 shows a diagram of the fundamental components. The volume of compressed air is controlled by partially filling the tank with water. When the air-actuated plug valve is opened, air rushes into the tube and builds up a pressure on the mylar diaphragm. The diaphragm bursts, resulting in a sudden pressure-rise on top of the sand and a restricted airflow into the plenum. When the air-actuated plug valve opens, two relief valves also open, causing the pressure on the sand to drop quite rapidly. As a result of this sequence of operation, the pressure immediately above the sand reaches a peak in 20 to 45 milliseconds and then decays to almost zero within one to six seconds. Preliminary tests in the NCEL Atomic Blast Simulator in which the rise time was 4 milliseconds resulted in a gradual pressure rise below the sand, indicating flow phenomena; consequently the rise times of 20 to 45 milliseconds were considered satisfactory. The peak pressure obtained with the Air Blast Device is a function of the original pressure in the supply tank. Decay time is controlled by presetting the water level in the supply tank to adjust the volume of air and by partially opening the two gate valves to govern the rate of airflow from the tank. In an actual blast, the overpressure at any time can be closely represented by the empirical equation [1]

$$p(t) = p\left(1 - \frac{t}{t+}\right) e^{-t/t+}$$

where p(t) is the overpressure at any time, t, after the arrival of the shock front; p is the peak overpressure; and t+ is the duration of the positive phase of the blast wave. The pressure process represented by this equation may be approximated rather well by the equipment just described.

Pressure cells (strain gages) were installed in the plenum and a few inches above the sand filter. Rapid-response thermocouples were installed above and below the sand and in the plenum. Leads from both pressure cells and thermocouples were connected through amplifiers to a Consolidated Electrodynamic Corporation oscillograph which records on light-sensitive paper. A typical set of traces copied directly from an oscillograph record is shown in Figure 4; since the traces are made by tiny rays of light which produce solid lines on the paper, their positions must be separated at the origin in order to identify them.

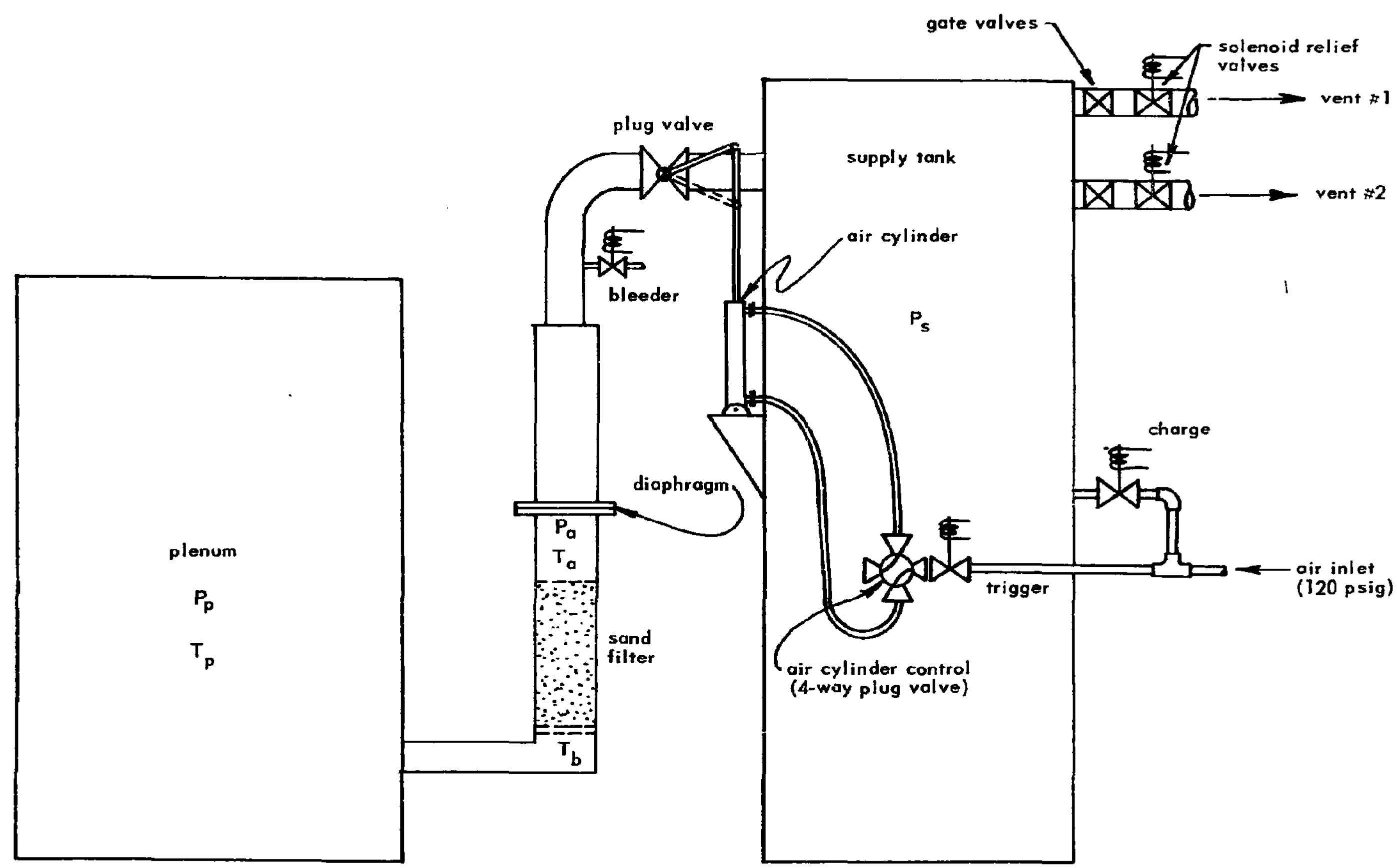


Figure 3. Diagram of model and Air Blast Device.

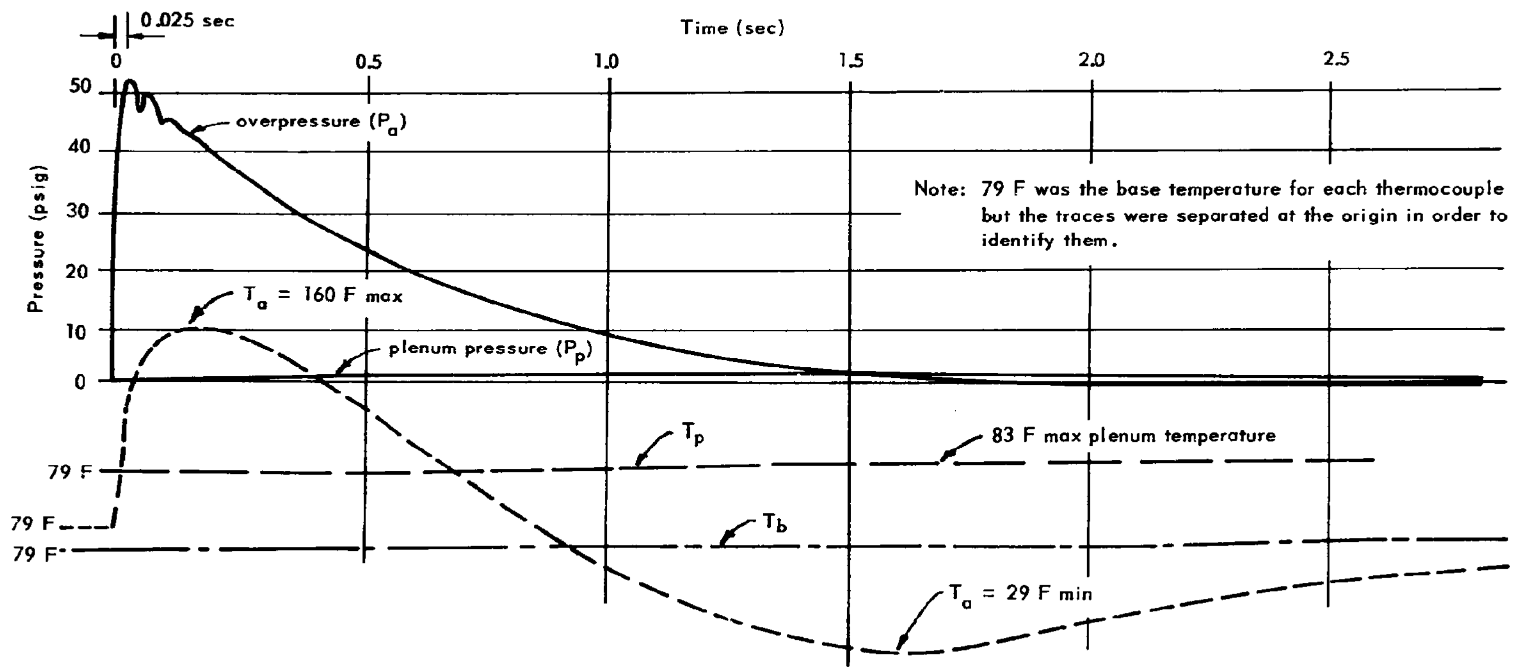


Figure 4. Traces copied from oscillograph record.

Test Procedure

The tests on the blast attenuation of the filter were done in three sections: A, B, and C. Section A was an extensive test of an 8-inch diameter filter. The size of the sand grains conformed to the Artos specifications. Section B, although similar to A, was less extensive and used a 12-inch diameter filter. Section C was a test of the 8-inch diameter filter, but the sand gradations were carefully controlled. In all tests, the sand was kept dry and was compacted by tapping the outside of the filter with a hammer. The following information was collected:

$p_s$ — pressure in supply tank before shot

$p_a$ — pressure immediately above sand

$p_p$ — pressure in plenum

$t_a$ — temperature immediately above sand

$t_b$ — temperature immediately below sand

$t_p$ — temperature in plenum

Section A Tests. The sand used in the Section A tests was taken at random from a batch graded as follows: 80 to 90 percent from 1 mm to 3 mm; 5 to 15 percent from 2 mm to 1 mm; and 0 to 5 percent less than 2 mm.

The Section A tests conducted are tabulated as follows:

| Plenum Volume ($ft^3$) | Filter Diameter (in.) | Filter Depth* (in.) | Overpressure** (psi) | Time Duration (sec) |
|---|---|---|---|---|
| 30, 45, 60 | 8 | 12, 24, 36 | 15, 30, 45<br>60, 75, 100 | 2 |

* These depths were used with each plenum volume.
** These values of overpressure were applied to each filter depth.

Section B Tests. The sand prepared for the Section A tests was also used in the Section B tests of a 12-inch-diameter filter.

The Section B tests are tabulated as follows:

| Plenum Volume ($ft^3$) | Filter Diameter (in.) | Filter Depth* (in.) | Overpressure** (psi) | Time Duration (sec) |
|---|---|---|---|---|
| 105 | 12 | 24, 36 | 15, 30, 45<br>60, 75, 100 | 2 |

* Each filter depth tested with the one plenum volume.
** These values of overpressure were applied to each filter depth.

Section C Tests. The Artos Machinery Company specified that 80 to 90 percent of the sand should be between 1 to 3 mm; up to 15 percent between 0.2 and 1 mm; and 0 to 5 percent less than 0.2 mm. Without a normal distribution, one sample of sand might have a preponderance of particles close to 3 mm, and another sample might be largely 1 mm plus the maximum percentage of finer particles. To study the effect of such abnormal particle distributions, the following two samples were tested:

| Sample | U. S. Sieve No. | Particle Size (mm) | Percentage |
|---|---|---|---|
| 1 (coarse)* | 6-8 | 2.38 - 3.36 | 100 |
| 2 (fine)** | 12-16 | 1.19 - 1.68 | 90 |
| | 50-60 | .25 - .30 | 5 |
| | 60 and smaller | .25 and less | 5 |

* See Figure 5
** See Figure 6

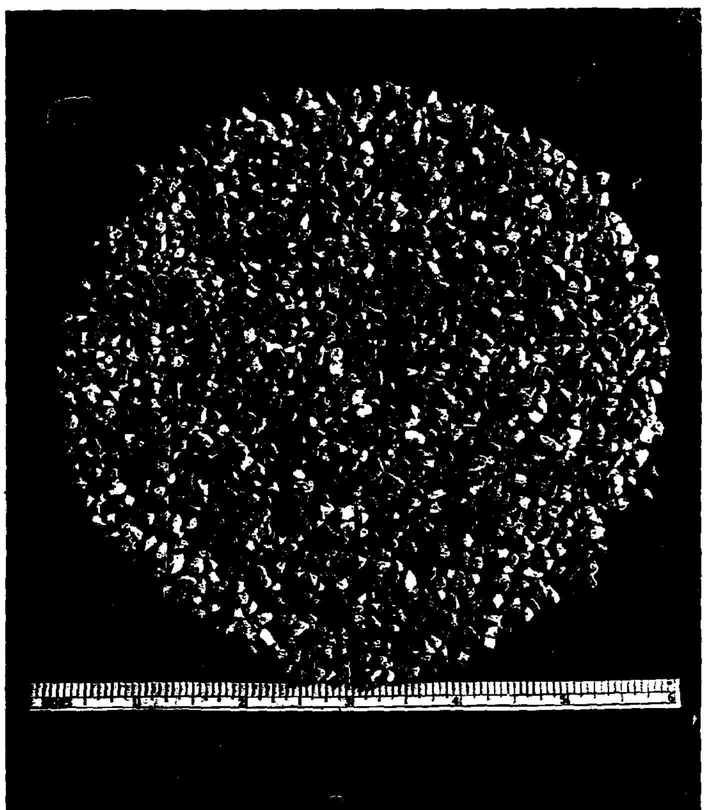

Figure 5. Sample of coarse sand.

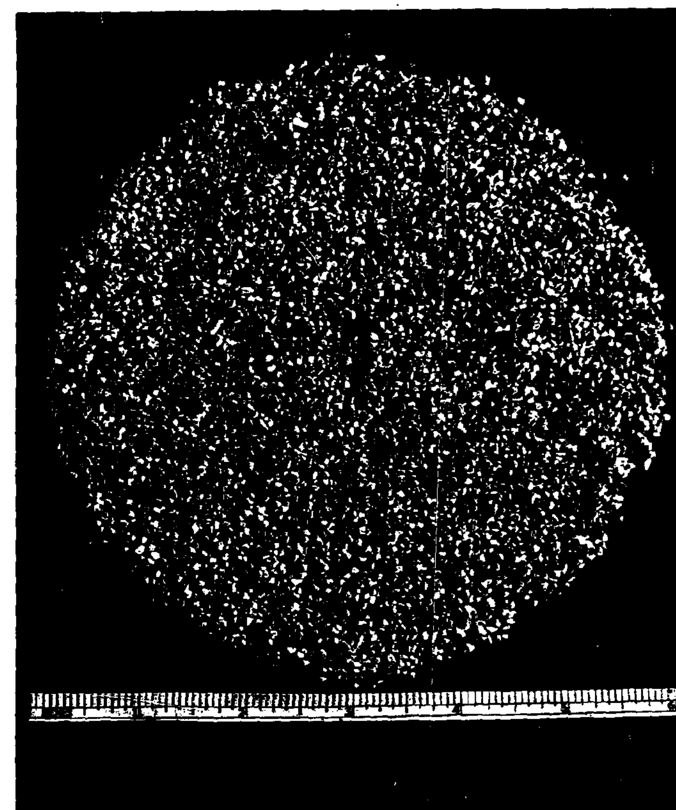

Figure 6. Sample of fine sand.

The Section C tests on each of the samples above are tabulated as follows:

| Plenum Volume ($ft^3$) | Filter Diameter (in.) | Filter Depth* (in.) | Overpressure** (psi) | Time Duration (sec) |
|---|---|---|---|---|
| 30, 45 | 8 | 36 | 80, 100 | 2 |

* This depth tested with each plenum volume.
** Both values were applied to filter.

It should be noted that in Section A, B, and C tests, the overpressures and time durations could not be controlled accurately so the values shown are only approximate.

Test Results

Figures A-1 through A-4 in Appendix A, show the curves of plenum pressure versus overpressure for the Section A tests. Figure A-5 shows the curves of Section B tests, and Figures A-6 and A-7 show curves of the Section C tests.

It was assumed that the most useful way to present the data would be to plot plenum pressure versus overpressure. This could not be done directly because the duration of the shock would have to be the same for all shots, and it was not practical to obtain uniform time durations. However, impulse combines the time with overpressure and values for impulse were plotted against plenum pressure. It was then easy to work backwards and obtain the values to plot plenum pressure versus overpressure at the prescribed time duration of 2 seconds. An example showing how this correction procedure was done is given in Appendix B. Table B-1 in Appendix B is a typical set of data, and Figure B-1 is a graph showing plenum pressure versus impulse. The resulting plenum pressure versus overpressure for this set of data is shown in Figure A-3.

The Section B tests were made to determine whether a larger size filter connected to a larger plenum would show any unexpected results which could be attributed to effects from the wall of the filter or to other flow phenomena. The 49-square-inch filter area and 45-cubic-foot plenum volume used in the Section A tests were a little more than doubled for this experiment, but the results revealed nothing unusual. In Figure A-5, there are small and inconsistent differences in plenum pressure as compared with the Section A tests, but these differences are probably due to sand distribution as determined in the Section C tests.

The results of the Section C tests show that the airflow through the sand varied considerably as the size distribution of the grains was changed, even though the distribution remained within the specifications of the Artos Machinery Company. The fine sand and the specified sand both meet specifications. The coarse sand contains 100 percent of the largest grains, but, even so, it comes close to meeting the specifications.

Figure A-6 emphasizes how the samples differed from each other in resisting the blast. At 100 psi overpressure (2 seconds duration), the fine sand permitted a pressure rise of only 3 psi in the plenum. On the other hand, the coarse sand permitted a pressure rise of over 9 psi in the plenum. It is evident that a modest change in particle size causes a marked change in the blast-attenuating properties of the sand. In view of the fact that sand has a natural tendency to segregate and in view of the fact that 90 percent of the Artos sand can be as large as 3 mm or as small as 1 mm, it is not surprising that every batch has its own characteristics. Consequently, if a sand filter is to be used in higher overpressure regions, e.g., 100 psi at 2 seconds duration, the sand must be carefully graded. If a sand filter is to be used in low overpressure regions, e.g., 25 psi at 2 seconds duration, the Artos sand or similar commercial grades would be satisfactory. The time duration is of course extremely important when considering the sand as a blast attenuator. Since the sand is not a closure device, it can only retard the airflow, it cannot exclude it. The cost of carefully graded sand is approximately six times greater than Artos-type sand. As for other sands, such as those from beaches or dry river beds, it would seem to be a dangerous practice to use them. Probably the only safe approach to the whole problem would be to pretest the filter as a unit or to carefully grade the sand and match it against control samples.

The tests in this task have been very useful in giving an evaluation of the Artos Sand Filter. The results of the specified sand indicate that under minimum conditions* of ventilation and occupancy the filter would give blast protection** from a 1-megaton burst, to a shelter located 3500 feet or more from ground zero. In this instance the overpressure would be 100 psi and the time duration 1.4 seconds. It would probably give protection from a 10-megaton burst, to a shelter located 10,000 feet from ground zero, in which case the overpressure would be 50 psi and the time duration 2.8 seconds.

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* 3 cfm fresh air per person and 66 cubic feet of space per person

** Blast protection here assumes a 5-psi maximum-allowable pressure rise in the shelter[2]

## CHARACTERISTICS OF SAND FILTERS WITH RESPECT TO ABSORPTION AND DISSIPATION OF HEAT

### Hot-Blast Tests

If a shelter with a sand filter were tested in the field with a nuclear blast of 100 psi, the temperature of the air striking the filter would be about 730 F* at the time of maximum pressure. The air would then expand isentropically causing the temperature to drop to about 200 F by the end of the positive phase of the blast.

The temperatures recorded at peak overpressures in the blast-attenuation tests were lower than the theoretical values so a series of tests was made using preheated pressurized air. Figure 7 shows the equipment, including a 3.7-cubic-foot tank which was mounted horizontally and connected to the top of the 8-inch shock tube. Inside the tank, four heaters controlled by a variable transformer heated the air. The location of thermocouples and pressure cells is shown in Figure 7. The filter was 36 inches deep and the plenum volume was 45 cubic feet.

Four shots using heated air were made at 15-minute intervals in order to study the movement of the temperature gradient through the sand. The results are shown in Table V. All shots indicated good simulation of the pressure decay curve. Although the temperature of the air dropped sharply as it expanded from the hot tank, it dropped at a slow rate after striking the sand. Consequently, the tests were reasonably severe. After the four shots, the temperature measured at 2 inches below the sand surface had risen from ambient to 260 F, but at 6 inches below the surface the maximum temperature recorded was only 83 F. During this same period, the temperature 24 inches below the surface had actually dropped from 63 F to 61 F. The thermodynamic processes in the sand filter are probably as follows: the first few inches of sand quickly absorbs heat from the high-temperature air, and, as it passes through the sand, the air cools still further from expansion. However, the sand prevents the air from cooling more by adding heat when the temperature of the air is lower than that of the sand. The process is, therefore, not adiabatic but one in which the sand moderates the air temperature because of its relatively large heat-storage capacity. Thus, it seems doubtful if a blast of 100 psi overpressure at 730 F would offer any temperature hazards to the occupants of a shelter protected with a 36-inch sand filter.

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* Temperature calculated from Hugoniot equation

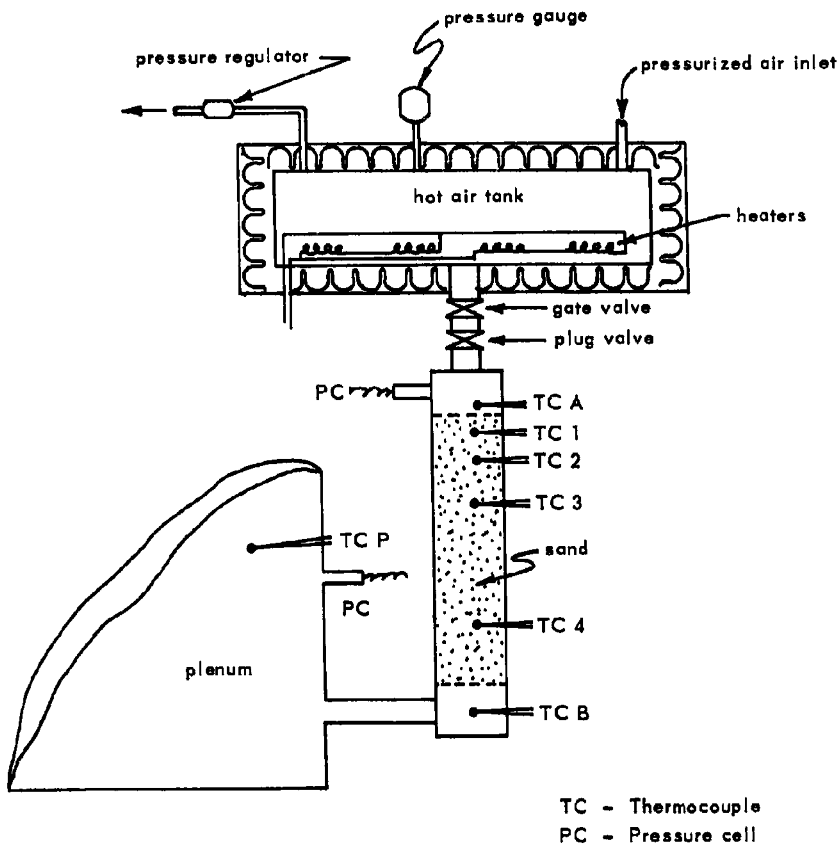


Figure 7. Hot-blast equipment.

Table V. Hot-Blast Shots

| | Shot 1 | Shot 2 | Shot 3 | Shot 4 |
|---|---|---|---|---|
| Temperature in hot air supply tank | 661 F | 655 F | 670 F | 668 F |
| Peak overpressure on sand | 68.8 psi | 83.2 psi | 77.6 psi | 77.2 psi |
| Duration of shot | 2.2 sec | 1.85 sec | 1.85 sec | 1.85 sec |
| Thermocouple temperature | | | | |
| A — above sand | | | | |
| before shot | 75 F | 88 F | 88 F | 90 F |
| maximum | 360 1/ | 363 1/ | 368 1/ | 369 1/ |
| end of shot | 258 | 250 | 275 | 275 |
| 1 — 2 in. below sand surface | | | | |
| before shot | 69 | 162 | 208 | 238 |
| end of shot | 93 | 206 | 232 | 260 |
| 2 — 6 in. below sand surface | | | | |
| before shot | 65 | 67 | 69 | 75 |
| end of shot | 65 | 68 | 72 | 83 |
| 3 — 12 in. below sand surface | | | | |
| before shot | 60 | 61 | 62 | 63 |
| end of shot | 60 | 61 | 62 | 64 |
| 4 — 24 in. below sand surface | | | | |
| before shot | 63 | 63 | 62 | 61 |
| end of shot | 62 | 62 | 61 | 61 |
| B — air below sand | | | | |
| before shot | 61.5 | 61 | 60 | 59 |
| end of shot | 60 | 58.5 | 57 | 56.5 |
| P — air inside plenum | | | | |
| before shot | 67.5 | 71.5 | 71 | 72 |
| end of shot | 88 | 86 | 80.5 | 78 |
| Pressure rise in plenum | 3.8 psi | 4.4 psi | 4.1 psi | 3.9 psi |

1/ A temperature of 360 F is associated with a shock-wave overpressure of approximately 40 psi.

Controlled Temperature Ventilation Tests

When hot air is drawn through a buried sand filter, it may be assumed in advance that the sand will act as a moderator to prevent the ventilating air from entering the shelter at a high temperature. Its effectiveness in this respect depends on its ability to absorb heat from the air, and then reject it to the surrounding soil or to subsequent cool air. Some soils have a high resistance to heat flow, in which case the absorbed heat would be retained by the sand until slowly carried into the shelter by the cooler air. Conversely, some soils have a low resistance to heat flow, in which case the absorbed heat would be readily transferred to the soil enhancing the action of the sand as a moderator. Figure 8 illustrates the equipment with which warm air was passed through the filter.

The filter was wrapped with 1 inch of fiberglass insulation. Four tests were run at different airflows and inlet temperatures. Complete data can be seen by examining Table VI and Figures 9, 10, 11, and 12. The significance of 1.3 cfm and 3.5 cfm is their relationship to static pressure drop across 3 feet of sand. The lower value corresponds to approximately 1 inch of water and the higher value to 2.5 inches of water. The entering air temperatures in Tests 1, 3, and 4 are presumably more rigorous than any situation which would be encountered in an actual situation. Calculations were made to determine how much heat the filter could reject to the soil. Two soils were considered: soil A, having a thermal conductivity of 0.22 Btu/hr/sq ft/(deg F/ft) and thermal diffusivity of 0.011 sq ft/hr; and soil B, having a thermal conductivity of 0.80 and thermal diffusivity of 0.024. Ingersoll's[3] formula was used in the calculations, assuming that the soil had been absorbing heat from normal ventilation for two weeks. Other pertinent factors are given in Table VI.

The results of the four tests have been summarized in Table VI and Figures 9, 10, 11, and 12. In all cases the ability of the sand to absorb heat was excellent. It can be seen from item 12 in Table VI that soil A would be unable to absorb the total heat dissipated to the atmosphere. Item 13 indicates that soil B could absorb much more than the total heat dissipated.

If the sand filter for an actual shelter consisted of a large concrete container (Figure 13) much of the heat absorbed by the sand would be trapped in the center of the filter and carried into the shelter before it could be dissipated to the soil. Therefore, if it is the engineer's intention that the filter reject as much heat as possible to the soil, it would be necessary to use a pipe grid (Figure 14) or possibly a long narrow concrete container with a large amount of the surface exposed to the soil. The practice of drawing in heated air for shelter ventilation is questionable since this air may contain carbon monoxide from fires. The nontoxic environments which might develop as a result of fire are difficult to predict.

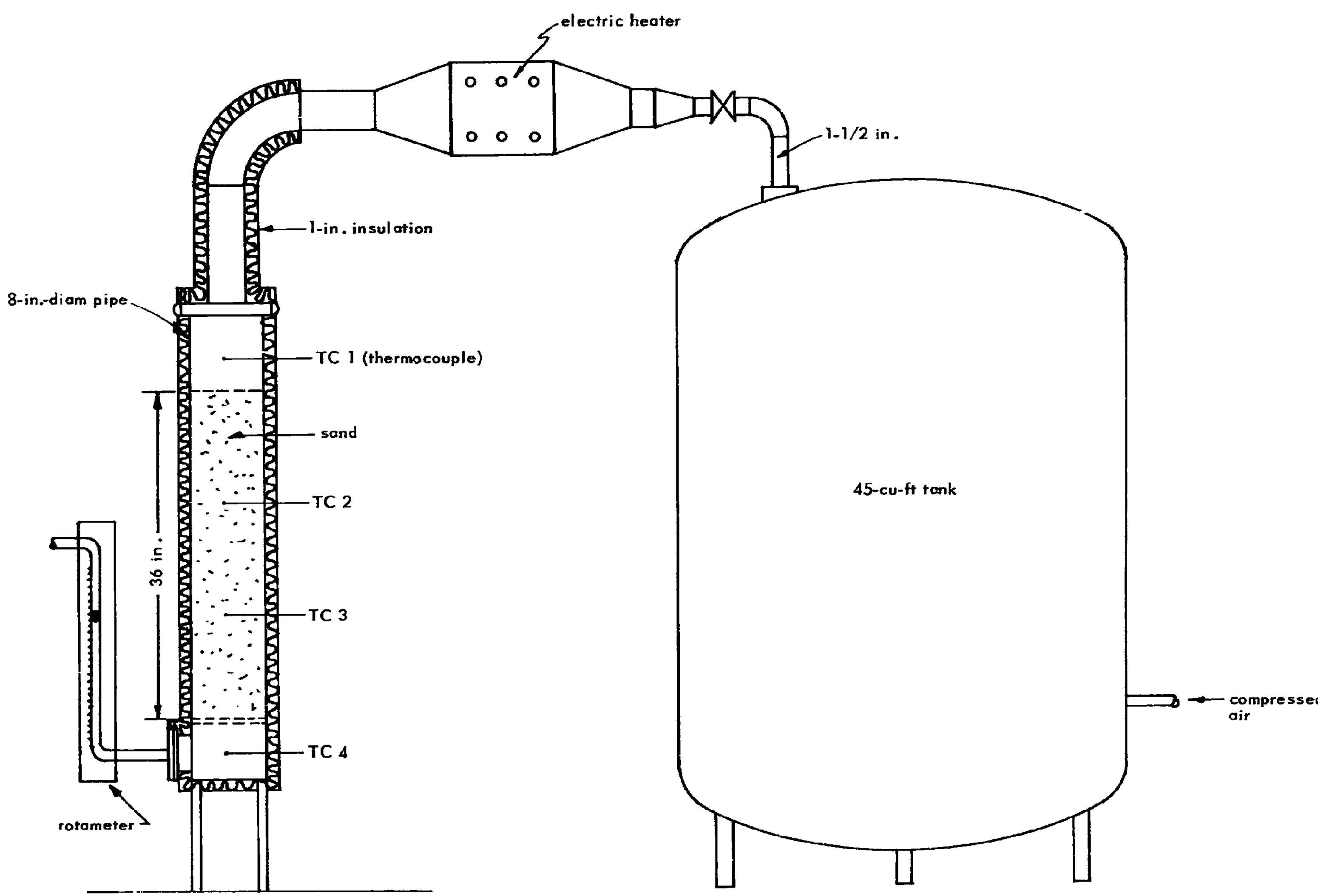


Figure 8. Controlled temperature ventilation test equipment.

Table VI. Results of 24-Hour Controlled Temperature Ventilation Tests

| | | | | |
|---|---|---|---|---|
| 1. Test | 1 | 2 | 3 | 4 |
| 2. Cfm | 1.3 | 3.5 | 3.5 | 3.5 |
| 3. Time of test (hr) | 24 | 24 | 24 | 24 |
| 4. Max temp of air entering (F) | 210 | 115 | 195 | 380 |
| 5. Max temp of air leaving (F) | 70 | 70 | 85 | 105 |
| 6. Mean temp of air entering (F) 1/ | 112 | 74 | 102.5 | 163.5 |
| 7. Mean temp of air leaving (F) 1/ | 64.5 | 60 | 71.2 | 83.3 |
| 8. Total heat entering filter via air (Btu) 2/ | 1750 | 1710 | 4320 | 9400 |
| 9. Total heat leaving filter via air (Btu) 3/ | 153 | 460 | 1470 | 2120 |
| 10. Residual heat in sand after test (Btu) 4/ | 195 | -97 | 136 | 390 |
| 11. Heat lost through pipe wall (Btu) (item 8 minus items 9 and 10) | 1402 | 1347 | 2714 | 6890 |
| 12. Capacity of soil A to absorb heat (Btu) 5/ | 1375 | 501 | 1330 | 2860 |
| 13. Capacity of soil B to absorb heat (Btu) 5/ | 4380 | 1580 | 4180 | 8980 |

1/ Mean temp equals datum temp plus the respective mean air temp rise. Datum temp was 55 F for tests 2 and 3 and 60 F for tests 1 and 4. Mean air temp rise in each case was computed from the area enclosed by the respective curve and datum line. Areas were measured with a planimeter.

2/ Based on mean temp rise of air entering.

3/ Based on mean temp rise of air leaving.

4/ Based on difference between sand temp at beginning and end of test.

5/ Based on a 3-ft length of 8-inch-diameter steel pipe. Soil temp assumed to be 55 F, and pipe temp assumed to be the average of items 6 and 7.

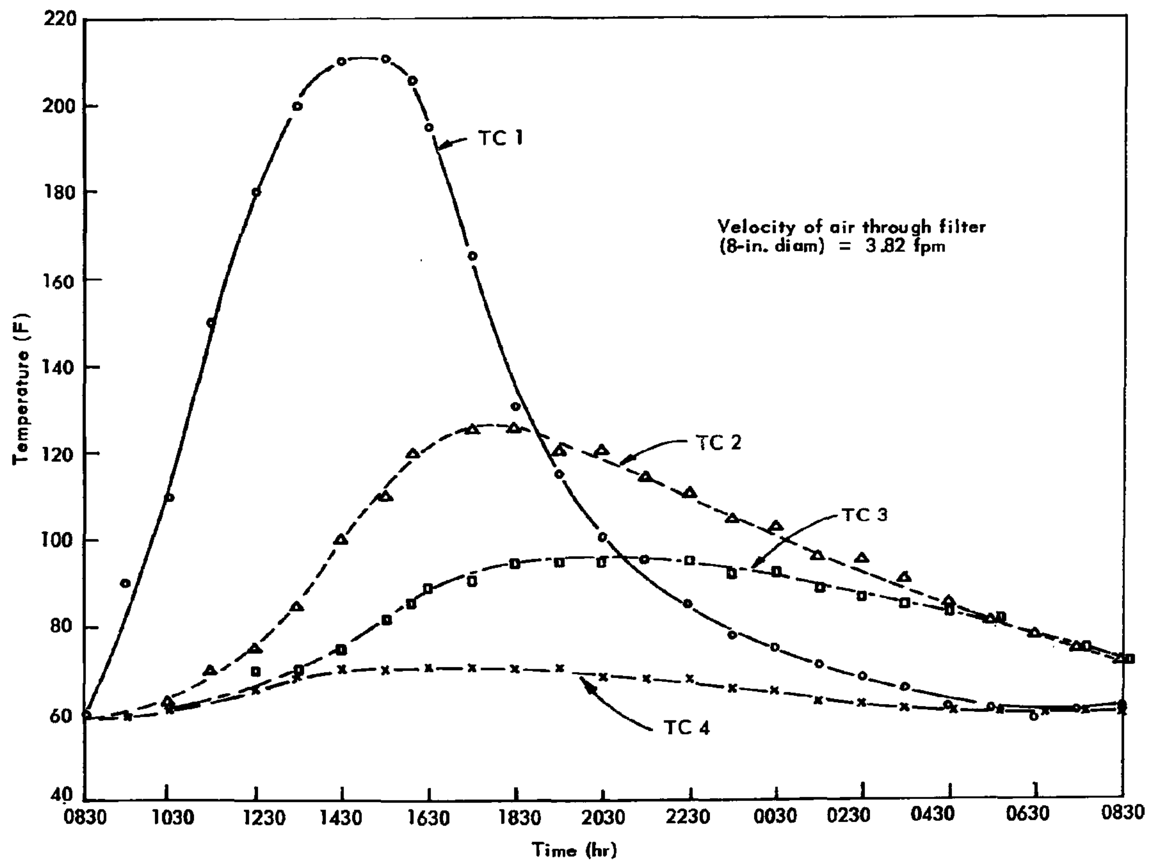


Figure 9. Test No. 1.

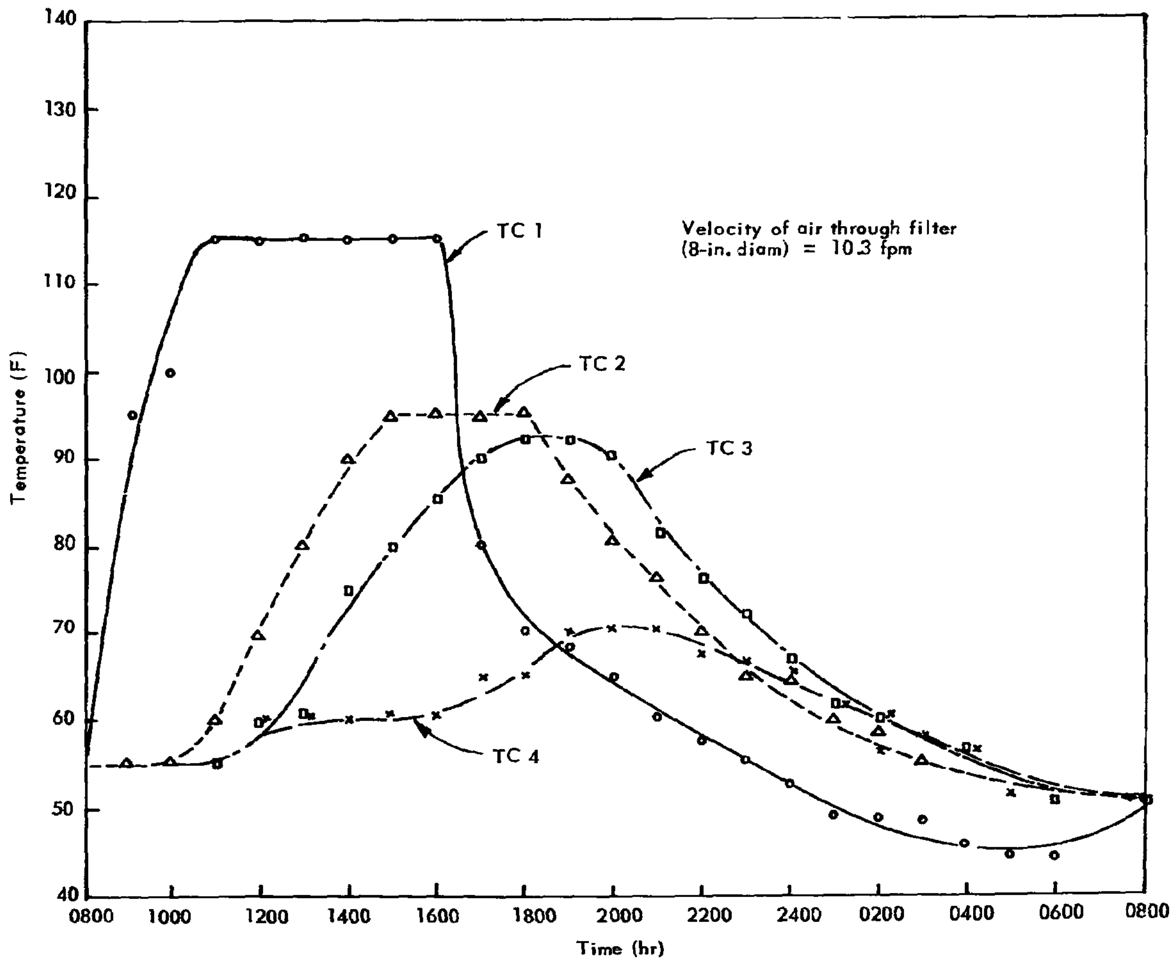


Figure 10. Test No. 2.

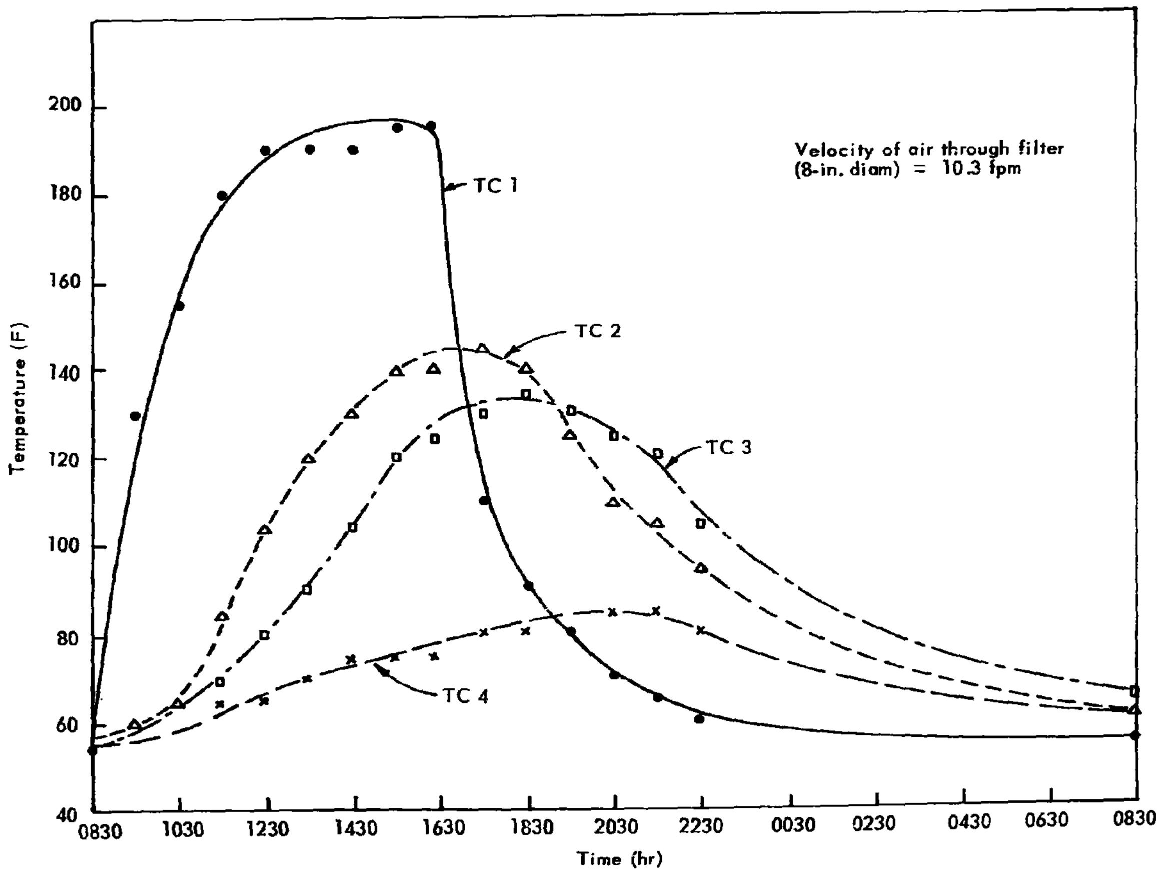


Figure 11. Test No. 3.

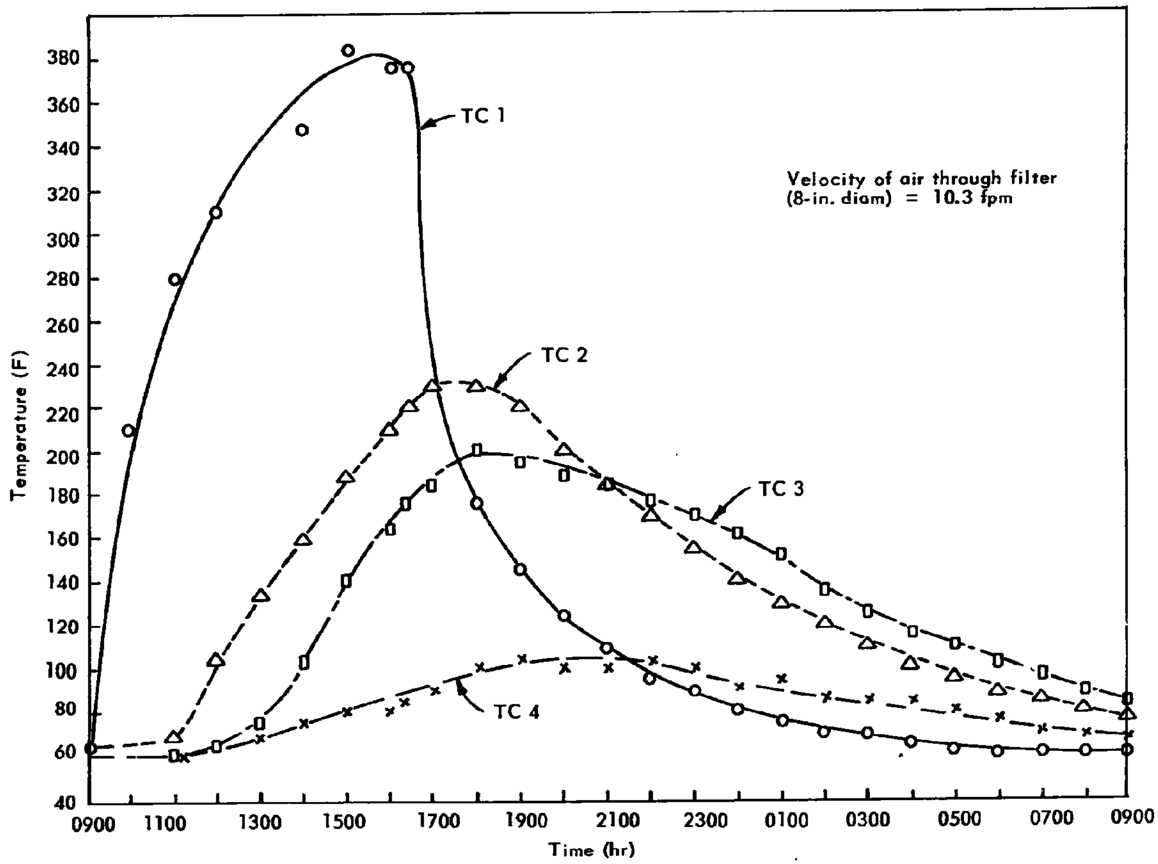


Figure 12. Test No. 4.

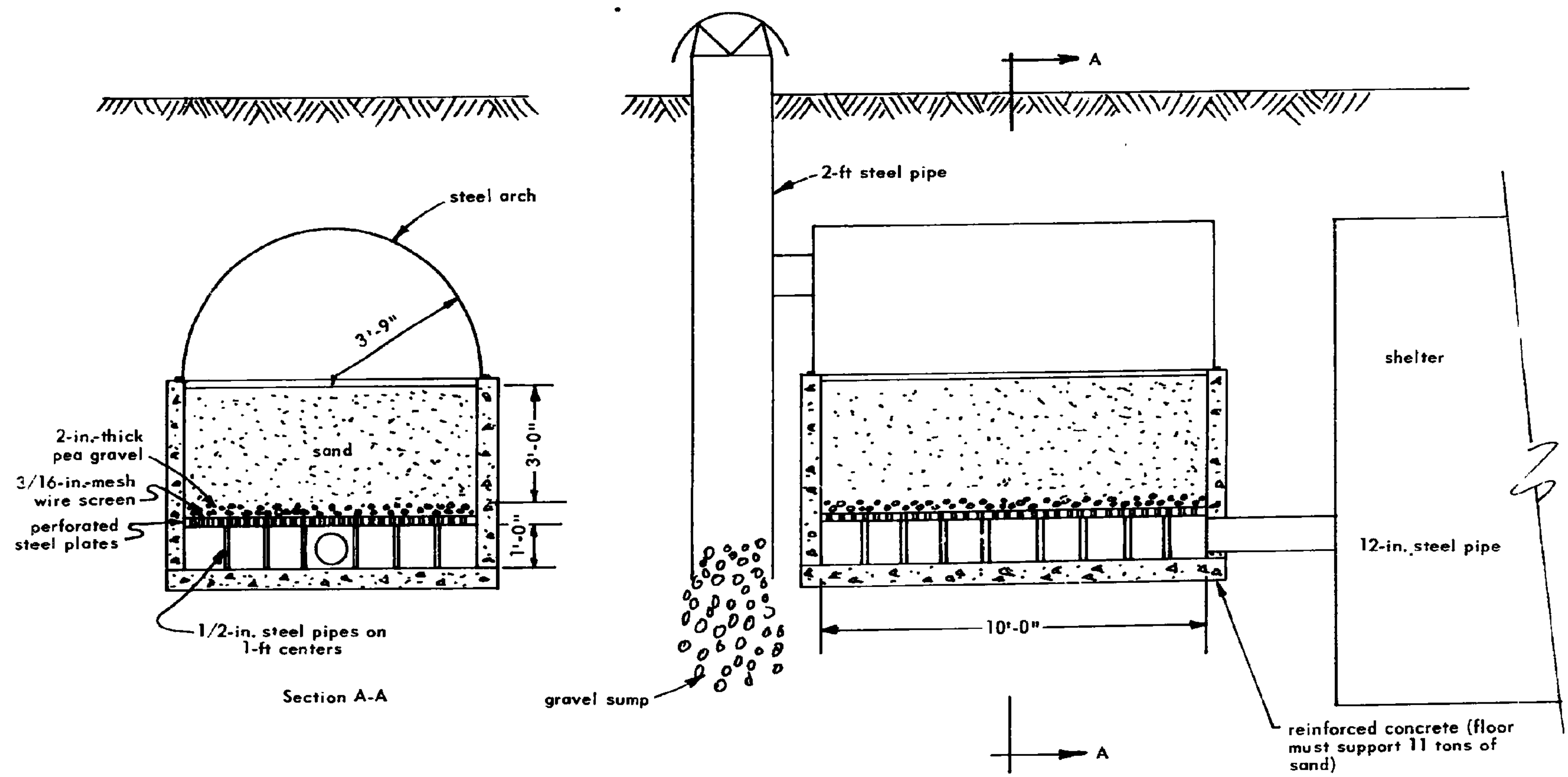


Figure 13. Sketch for a 300-cfm sand filter.

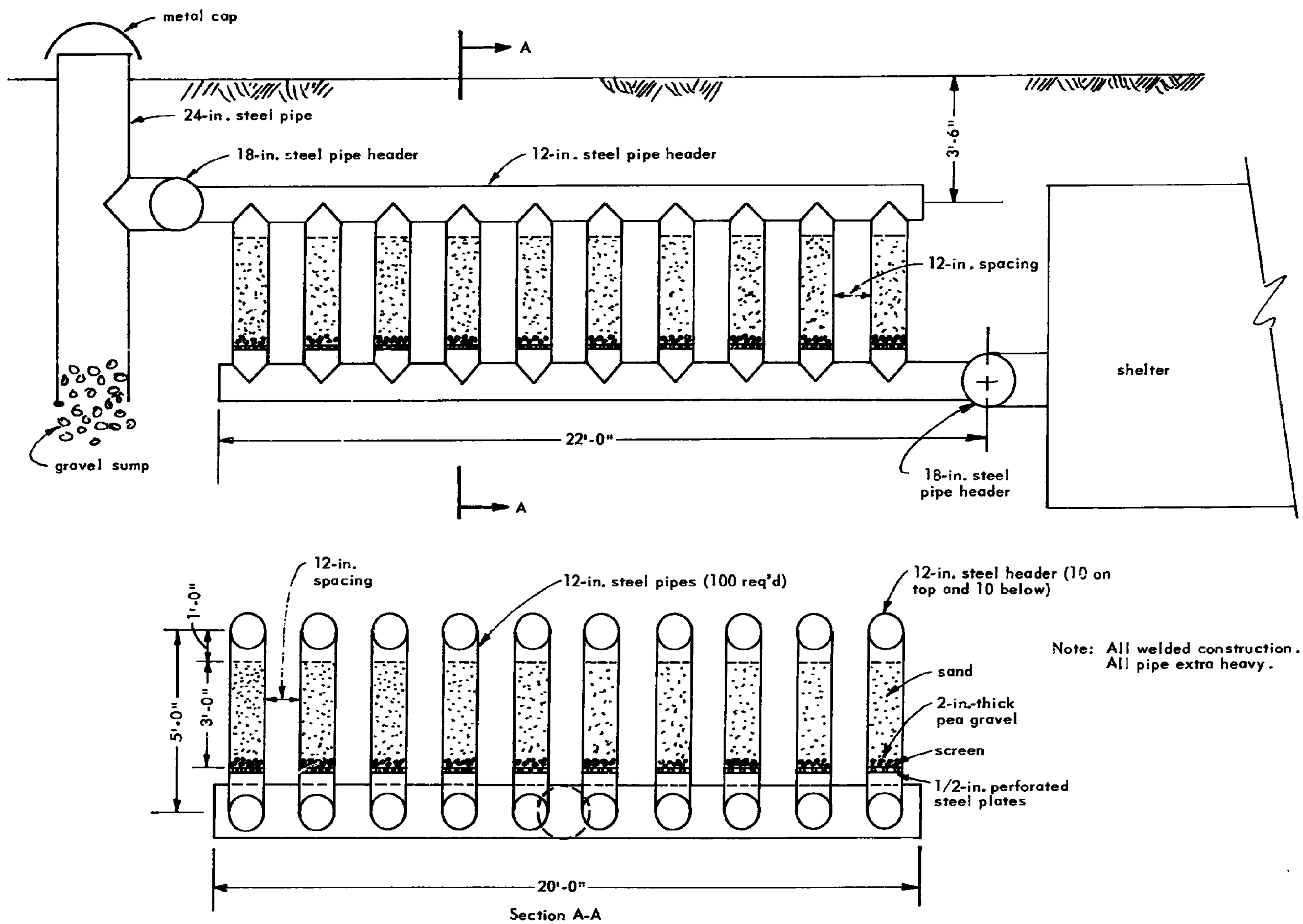


Figure 14. Sketch of heat sink for 300-cfm sand filter.

The estimated costs of material and construction for the filters shown in Figures 13 and 14 are \$4,000 and \$18,000, respectively.

It should also be mentioned that dry sand with its relatively low thermal conductivity effectively insulates the ventilation system against external heat when the system is not operating.

## CONCLUSIONS

1. Although the Artos sand filter will give significant blast protection against 1- and 10-megaton explosions, full knowledge of its capabilities would require further testing at longer durations.

2. Within the Artos specifications the effectiveness of the sand varies with changes in the size and distribution of the sand grains.

3. In low-pressure regions of medium time duration (25 psi at 2 seconds duration) Artos sand would be satisfactory, but in high-pressure regions of medium time duration (100 psi at 2 seconds duration) it would be necessary to use carefully graded sand.

4. The hot-blast tests gave good evidence that the sand can protect a shelter against the heat associated with overpressures up to 40 psi when the positive duration is two seconds or less, and can probably protect a shelter against a much stronger blast.

5. The controlled temperature ventilation tests showed that sand has excellent heat absorption capabilities. Calculations also indicate that a well-designed filter in certain types of soil would reject to the soil much of the absorbed heat.

6. The relatively high cost of a sand filter installation should be compared to the cost of other systems offering equal protection.

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Appendix A

BLAST ATTENUATION TEST CURVES

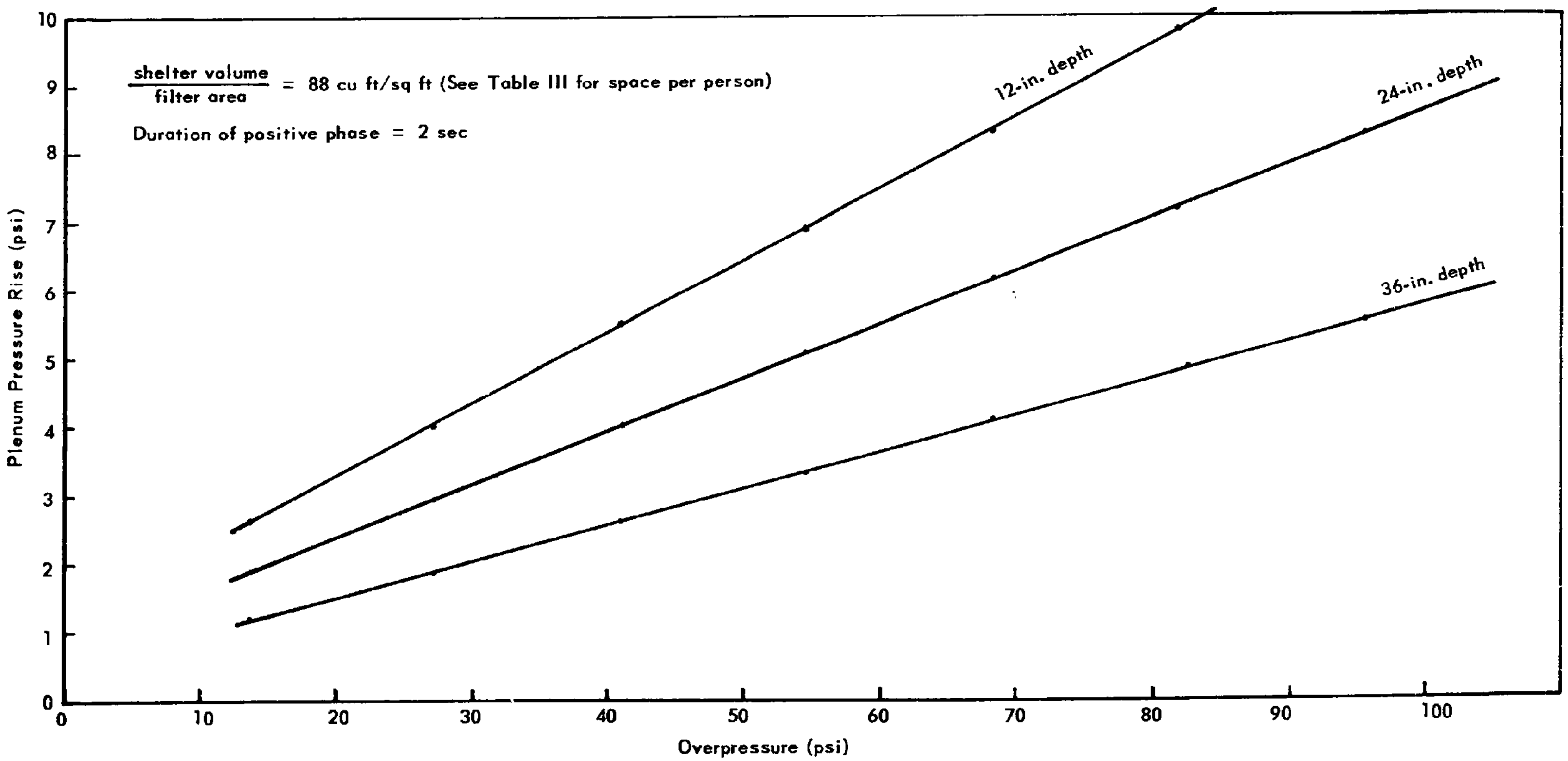


Figure A-1. Blast attenuation at different sand depths.

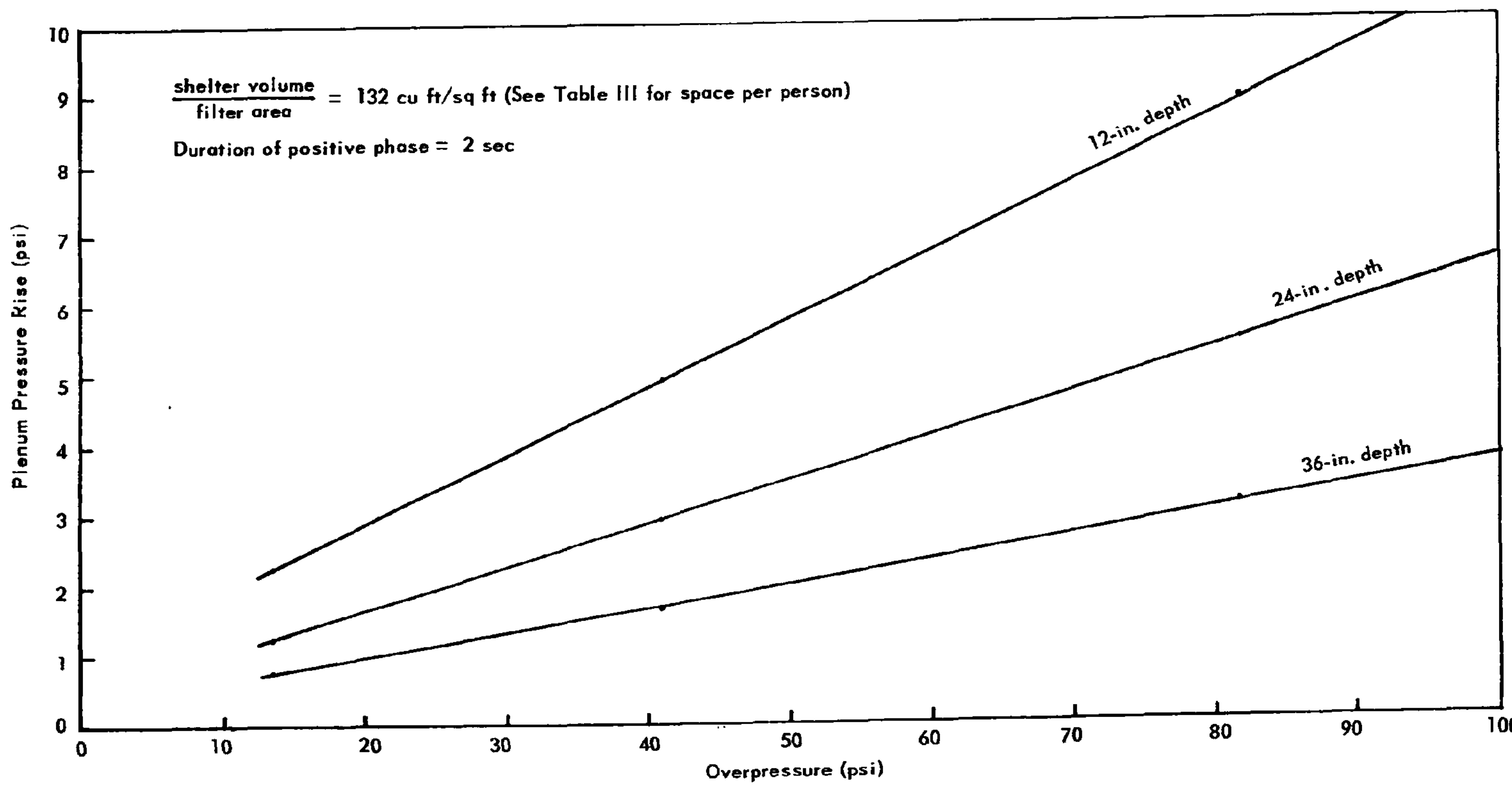


Figure A-2. Blast attenuation at different sand depths.

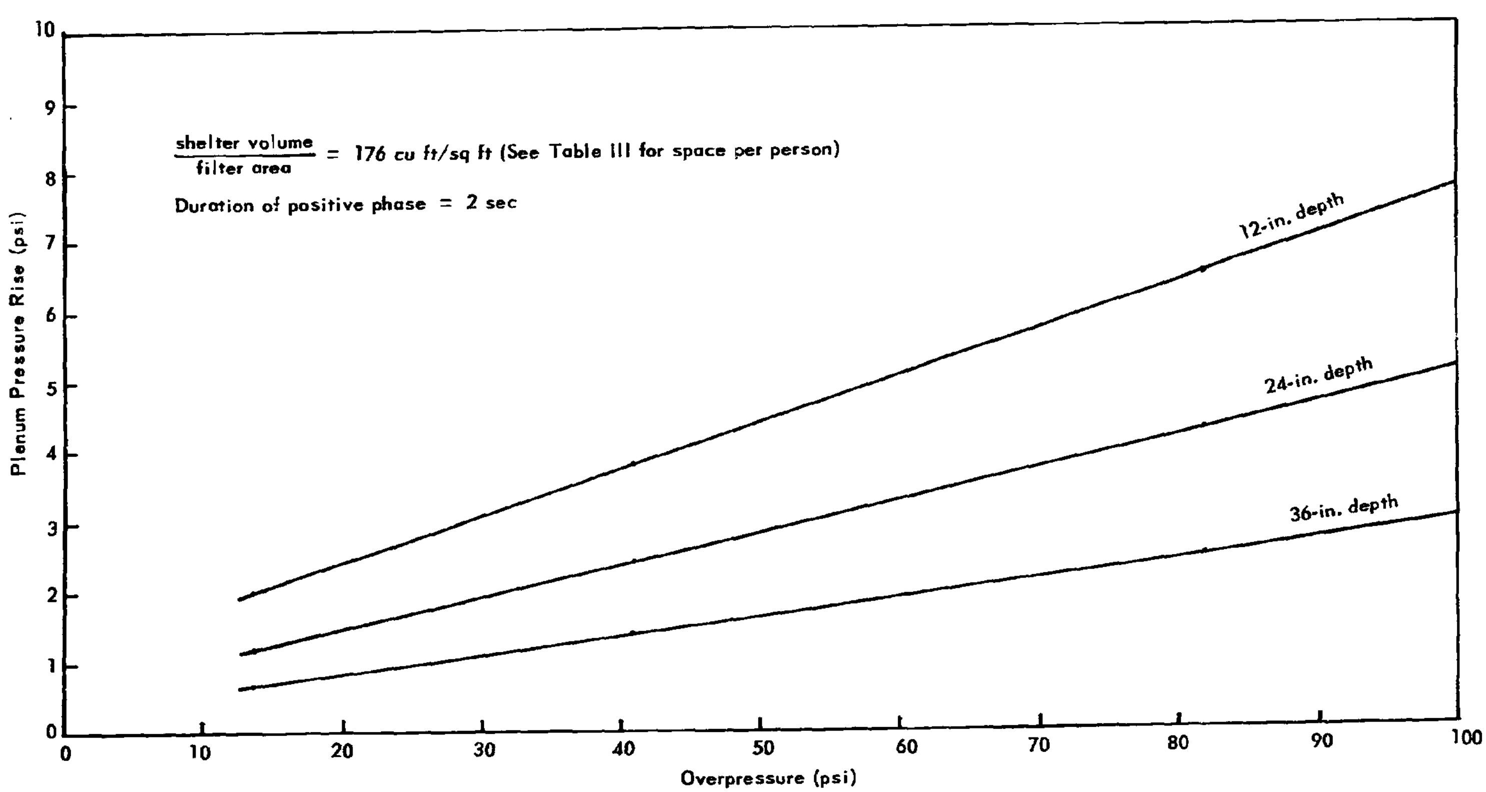


Figure A-3. Blast attenuation at different sand depths.

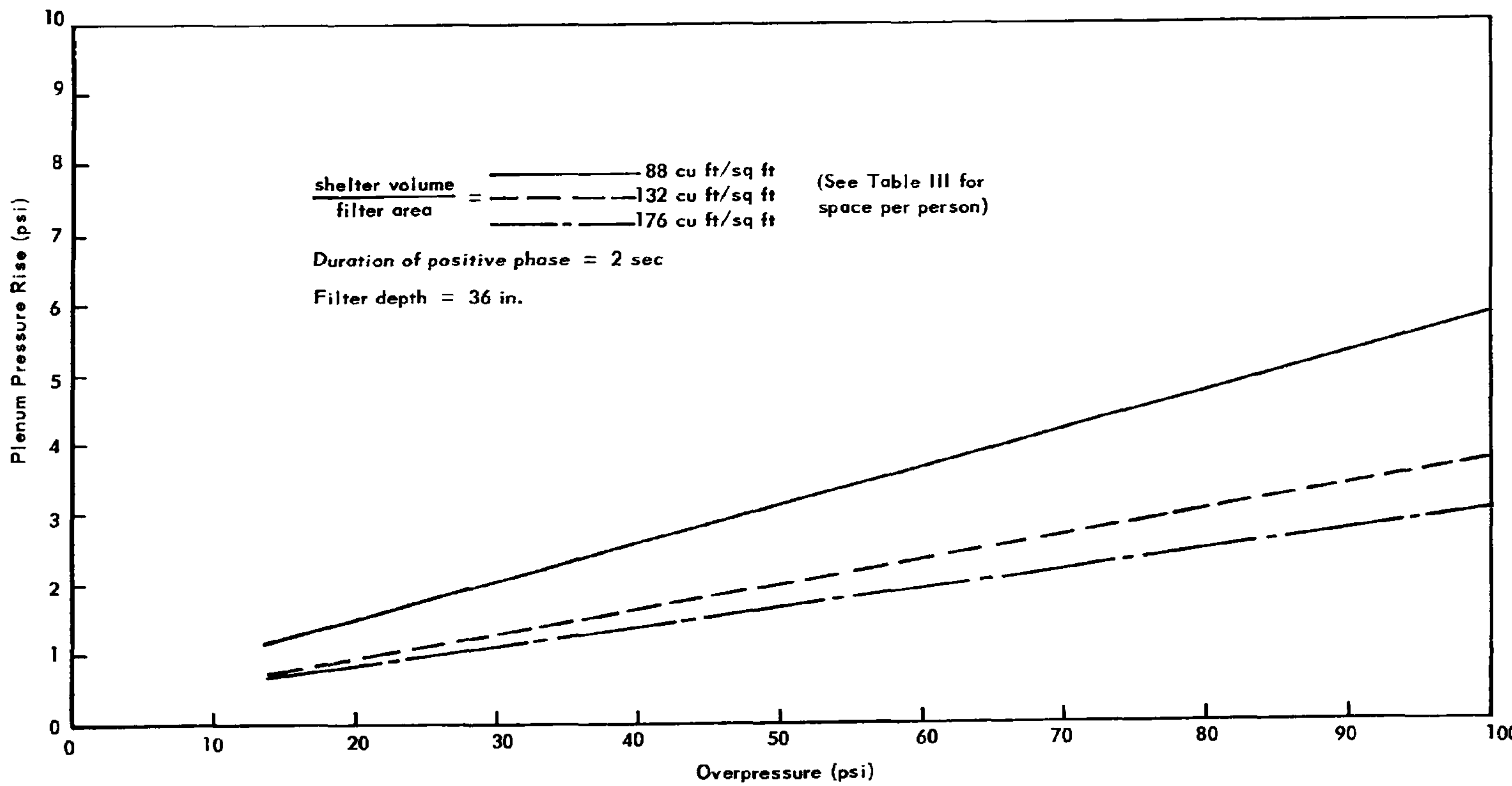


Figure A-4. Blast attenuation at different plenum volumes.

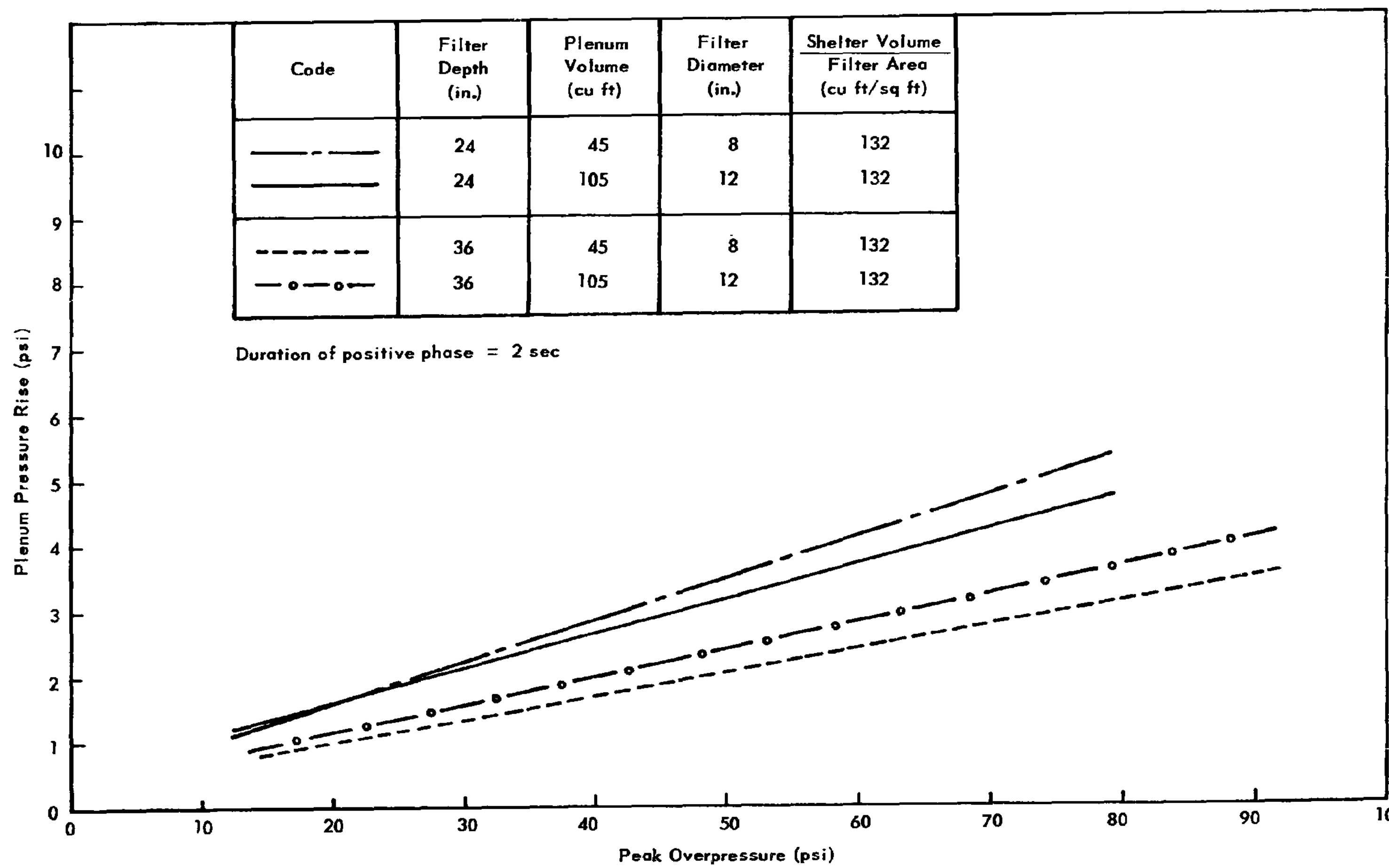


Figure A-5. Blast attenuation with enlarged plenum volume and filter diameter.

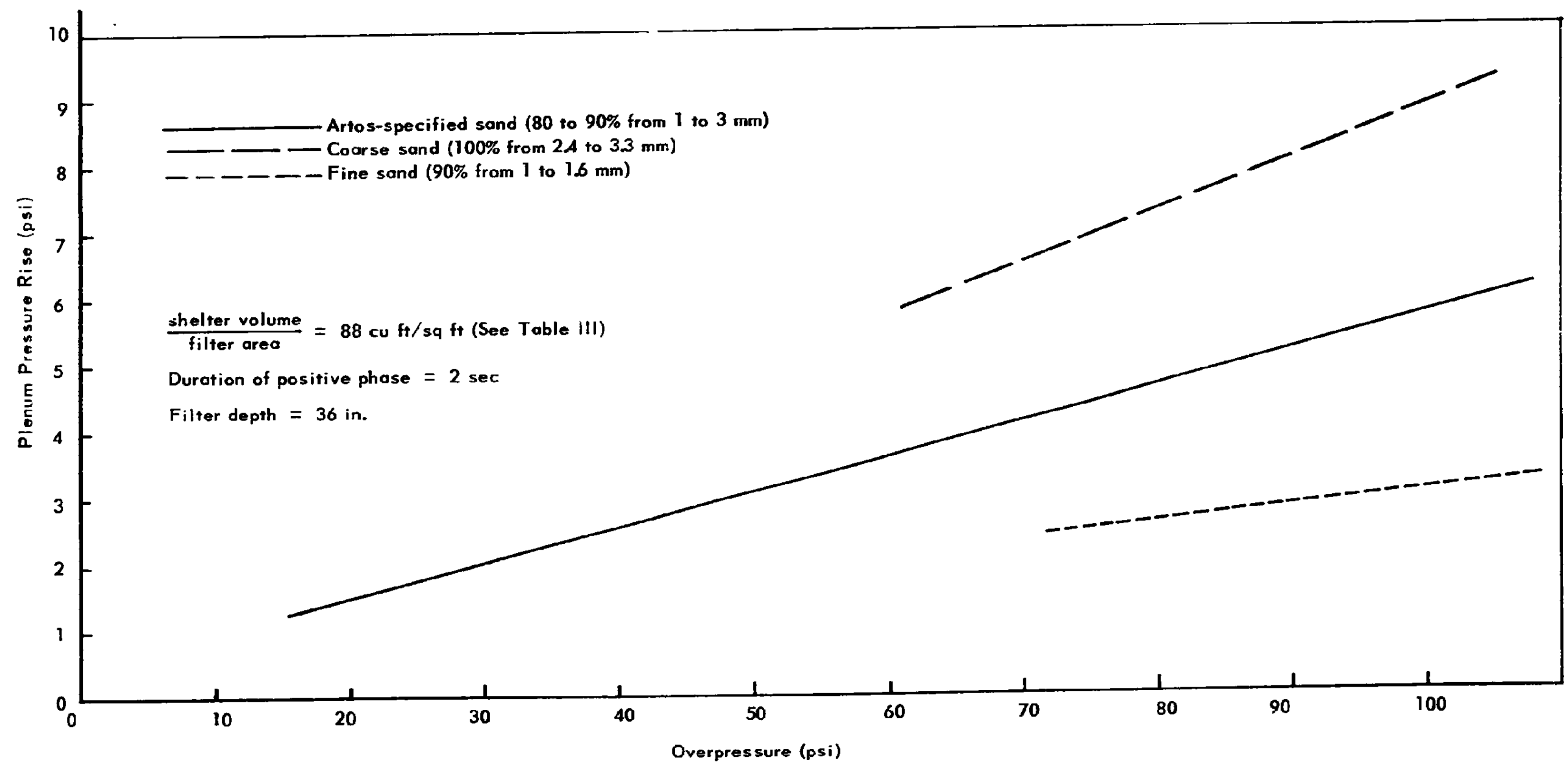


Figure A-6. Blast attenuation with different sand grain size and distribution.

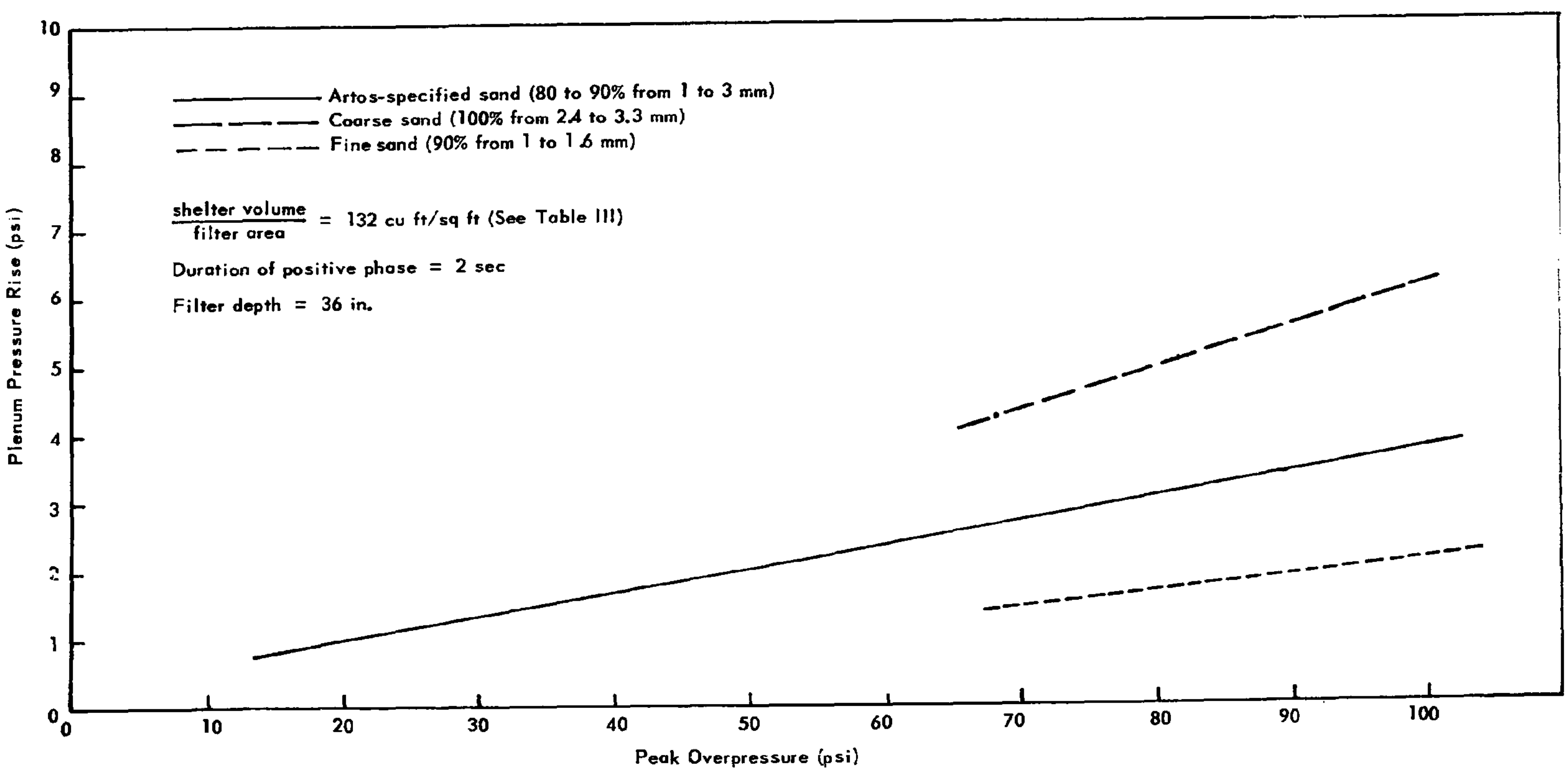


Figure A-7. Blast attenuation with different sand grain size and distribution.

## Appendix B

## SAMPLE DATA AND CALCULATIONS

The steps in obtaining values to plot plenum pressure versus overpressure were as follows:

1. For each shot, the time duration of the blast wave is combined with overpressure to give impulse using the formula[4]

$$I = \frac{tP_o}{e} \tag{1}$$

where $P_o$ = overpressure (psi)

$t$ = duration of the positive phase in seconds

$I$ = impulse (lb-sec/in.$^2$)

$e$ = 2.718

This formula is accurate at low overpressures but as overpressures are increased it gives impulse values which are higher than those of a nuclear blast.

2. The data for a typical series of shots is shown in Table B-I.

3. Values for plenum pressure are then plotted against impulse as shown in Figure B-1.

4. A linear regression is used to obtain the best straight line through the points. The equation for the line in Figure B-1 is

$$Y = 0.365 + 0.0362(X) \tag{2}$$

5. Values for plenum pressure and the corresponding impulse are then taken from this straight line. These quantities are listed in the first two columns of the following table.

Equation 1 with t = 2 seconds is used to compute the corrected overpressures.

| Impulse (lb–sec/in.$^2$) | Plenum Pressure (psi) | Overpressure (psi) |
|---|---|---|
| 10 | 0.7 | 13.65 |
| 20 | 1.1 | 27.3 |
| 30 | 1.4 | 41 |
| 40 | 1.8 | 54.6 |
| 50 | 2.2 | 68.2 |
| 60 | 2.5 | 81.8 |
| 70 | 2.9 | 95.5 |
| 80 | 3.25 | 109.0 |

6. The above values of plenum pressure and overpressure are plotted as shown in Figure A-3.

The linear equations for the other tests in which plenum pressure is plotted against impulse are as follows:

| Filter Diameter | Sand Depth | Plenum Volume | Equation |
|---|---|---|---|
| 8 | 12 | 60 | Y = 1.17 + .08915(X) |
| 8 | 24 | 60 | Y = 0.59 + .0617(X) |
| 8 | 12 | 45 | Y = 0.92 + .1323(X) |
| 8 | 24 | 45 | Y = 0.47 + .0833(X) |
| 8 | 36 | 45 | Y = 0.25 + .049(X) |
| 8 | 12 | 30 | Y = 1.1 + .1445(X) |
| 8 | 24 | 30 | Y = 0.83 + .105(X) |
| 8 | 36 | 30 | Y = 0.41 + .073(X) |
| 12 | 24 | 105 | Y = 0.35 + .056(X) |
| 12 | 36 | 105 | Y = 0.58 + .070(X) |

Table B-1. Data for Typical Series of Blasts

| Peak Over-pressure (psi) | Decay Time (sec) | Maximum Pressure in Plenum (psi) | Impulse (lb-sec/sq in.) | Initial Plenum Temp (F) | Max Plenum Temp (F) | Max Shock Tube Temp (F) | Min Shock Tube Temp (F) | Filter Exit Temp (F) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Before Shot | After Shot |
| 105.5 | 1.72 | 2.8 | 66.76 | 70 | 79 | 152 | 50.5 | 66.5 | 66 |
| 100 | 1.82 | 2.8 | 66.96 | 70 | 80 | 145 | 42 | 66 | 66 |
| 106 | 2.49 | 3.8 | 97.10 | 71 | 85 | 152 | 35 | 66 | 65.5 |
| 79.5 | 1.79 | 2.1 | 52.35 | 71 | 80 | 136.5 | 47.5 | 66 | 65.5 |
| 79.5 | 1.79 | 2.3 | 52.35 | 71 | 80 | 155 | 9 | 65 | 65 |
| 75.5 | 1.77 | 2.1 | 49.16 | 71 | 80 | 131 | 32 | 65 | 64.5 |
| 60.6 | 1.63 | 1.5 | 36.34 | 72 | 78 | 120 | 52 | 64.5 | 64 |
| 60.6 | 1.73 | 1.9 | 38.77 | 72.5 | 79 | 148.5 | 26 | 64 | 64 |
| 61 | 2.19 | 2.5 | 49.15 | 73 | 81 | 157.5 | 37.5 | 64 | 63.5 |
| 40 | 1.93 | 1.4 | 28.40 | 73 | 78.5 | 104 | 44 | 63.5 | 63 |
| 41.8 | 2.07 | 1.5 | 31.83 | — | — | 120 | 50 | 64.5 | 64 |
| 43.8 | 2.10 | 1.6 | 33.84 | — | — | 118 | 38 | 64.5 | 64.0 |
| 24.6 | 2.13 | 1.0 | 19.28 | — | — | 100 | 50 | 64.5 | 63.5 |
| 27 | 2.42 | 1.2 | 24.04 | — | — | 98 | 44 | 64 | 63 |

Note: Sand depth 36 in.; plenum volume 60 cu ft.

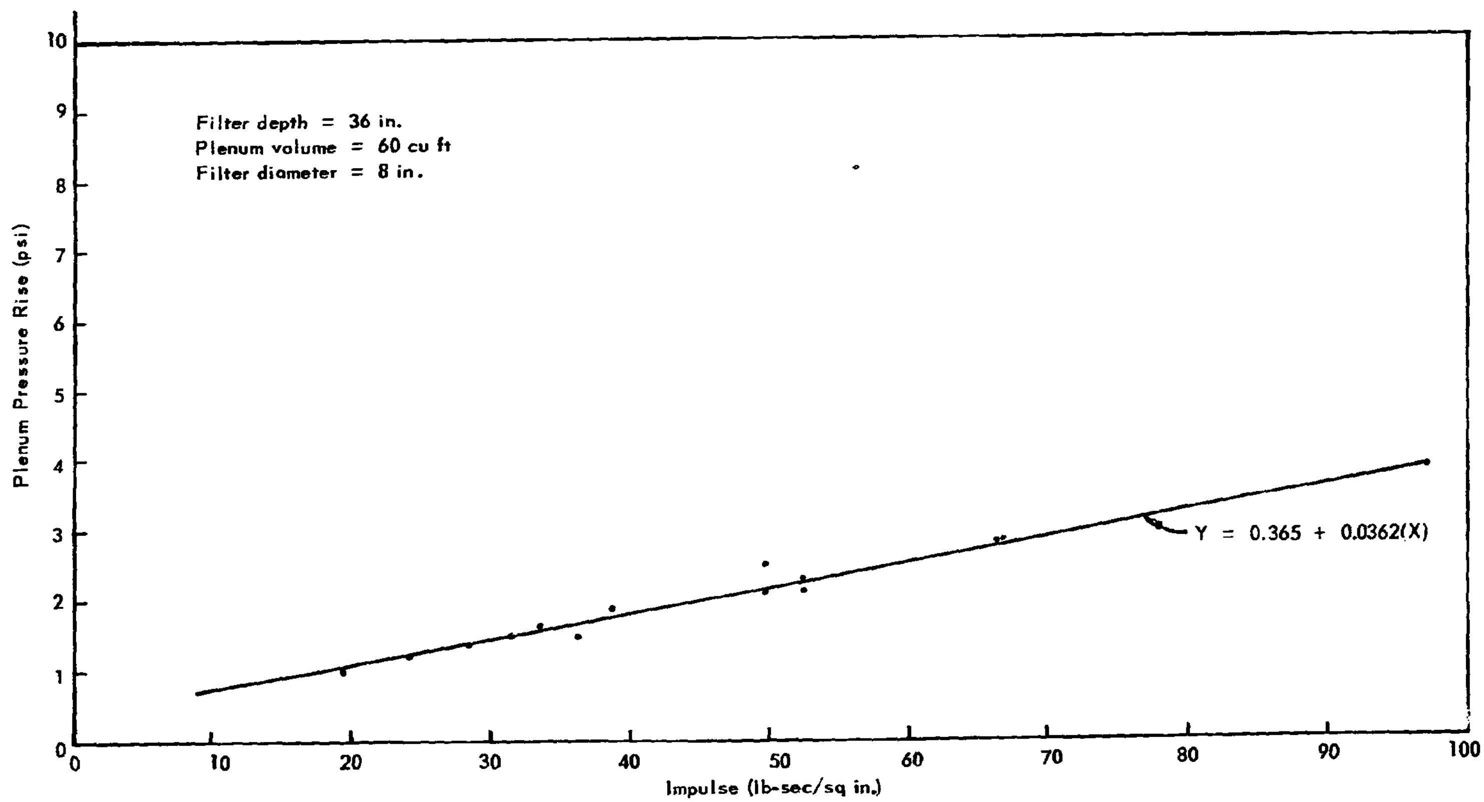


Figure B-1. Plenum pressure versus impulse.

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